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14. ABSTRACT Recent Collaborative work with the Naval Research Laboratory (NRL) to improve explosive detection using nuclear quadrupole resonance (NQR) is summarized. The work included aspects of radio-frequency (RF) mitigation particularly concerning RF coil design for NQR applications in the field, such as land mine detection. Additional studies involving three-frequency NQR were also pursued.						
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Improving NQR Detection of Materials

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This grant was in response to a proposal to NRL Broad Agency Announcement BAA 025, "Innovative Applications of Magnetic Resonance," following continued interaction with Dr. A. N. Garroway and his research group at NRL during the last several years. Four specific projects were proposed for study at MTU: three-frequency NQR, RFI remediation, target field calculations, and the use of receiving systems with no physical return path. These projects were to help address issues which arise for NQR detection of explosives, and in particular for detection of explosives in the field.

During the execution of this work, there was routine contact and interaction with Dr. A. N. Garroway and his research group at NRL, where results from these studies was presented and discussed. Rather than reproduce the details here, this document serves as a summary of those results. Additional details are available from the author, if needed.

Three-frequency NQR

For a spin-1 nucleus, such as ^{14}N , in a non-axial electric field gradient there are three distinct energy levels and transitions between all pairs are possible. That is, there are three transition frequencies. A typical NQR measurement will use only one of these transitions at a time. It was realized that there may be some advantage for materials detection applications if all three transition frequencies were used at the same time. In our case, two of the transitions are used to excite the nucleus and the third is used to detect a signal. By moving the detection frequency away from the excitation frequency(ies) various undesirable transient signals can be avoided.

Work on three-frequency NQR was a continuation of work initiated in a previous grant to include what we refer to as "secondary echoes." These are echo signals which are unique to the three frequency technique. The first three-frequency experiments performed using simultaneous radiofrequency (RF) excitation pulses (at NRL by K. Sauer in late 2000, using a probe initially provided by MTU) were, in essence, a way of reproducing single-frequency experiments using the double frequency excitation. That is, the desired signals obtained were the same as those which could have been obtained using a more traditional experiment. Sauer experimentally demonstrated reduction of spurious (undesirable) signals at the same time. By changing the way the excitation is done, additional signals can be obtained, which can not be obtained using a single frequency measurement and which provide information on the distribution of electric quadrupole fields within the material. Extensive measurements were made of these signals (again, at NRL mostly by K. Sauer) and, with some theoretical help from MTU, the signals were analyzed. The results were published in the Journal of Chemical Physics in 2003 (see

publications, below) which can be consulted for complete details.

RFI Remediation

Two distinct efforts for radio-frequency interference (RFI) remediation were considered: keeping the RFI out of the receiving system in the first place and finding ways to get rid of it once it has gotten into the system.

Many of the issues associated with removing RFI after it is received are under investigation by an Army "Red Team" working with Quantum Magnetics, Inc., San Diego, CA. The specific activities mentioned in the original proposal for this grant which were related to this were scaled back pending the outcome from the Red Team. Suits attended two meetings of the Red Team at QM's site to hear presentations related to improved RFI remediation for QM's vehicle-mounted NQR confirming sensor project. Copies of Suits' summary comments of those meetings were sent to A. N. Garroway (NRL) and Steve Schaedel (Army).

The work to keep the signal out of the system in the first place centers on the use of gradiometers. The principle work along these lines appears in two publications, one in the Journal of Applied Physics in 2003, and the other pending in Applied Magnetic Resonance, scheduled to appear in early 2004 (see "publications" below). The work presented in the Journal of Applied Physics is covered in the section "Target Field Calculations" below.

The more recent work which is to appear in Applied Magnetic Resonance, was a consideration of how signals might enter an NQR system in the first place. The result, in short, was that far-field interfering signals (such as from radio broadcasts) of the size actually observed can easily enter via a coupling to a magnetic (or electric) dipole moment of the NQR coil, even in cases where the coil has been constructed with the intention of not having such a moment. The ideal magnetic gradiometer of a size appropriate for land mine detection will not pick up a significant amount of interference. However, there are many ways in which a real gradiometer can develop an undesirable dipole moment of sufficient size to explain the observed levels of interference, even if one takes great care during construction. It is safe to say that for coils of the size used for land mine detection, if one is experiencing interference from far-field sources, then one is receiving it via a coupling to a dipole moment. To remove the interference, one would need to identify and remove that dipole moment.

Target Field Calculations

The idea behind a "target field calculation" is to specify a (magnetic) field which one would like to produce and from that compute an appropriate current density to produce it. Then a coil is designed which approximates that current density. The specified magnetic field must, of course, be allowed by Maxwell's equations. For land mine detection with a surface coil, it is not at all obvious what magnetic field one should specify. A method to determine allowed and optimized magnetic fields for surface coils was developed and presented in the Journal of Applied Physics (see "publications" and "new inventions" below). Gradiometer coils which were used for this study were "self-shielded" in a manner appropriate to guard against

interference from near-field radiation sources (which includes fields from far-field sources which are re-radiated by near-field objects). Since the near-field for ^{14}N NQR extends for roughly 100m, such sources could be an issue. (It is noted that at this time, there is no evidence known to us which suggests such re-radiated fields are a significant issue, at least compared to other sources of interference).

Coils without a return path

After some limited study, this line of research was terminated as a future "pay off" for explosive detection seemed unlikely. While it is clear that one can get signals in favorable cases, it is more difficult than using a standard coil and there will be significant technical issues related to the large RF electric fields which can be expected.

Publications related to this project:

(* indicates publication was pending at the end of the previous grant, and has now appeared)

"Remote Sensing by Nuclear Quadrupole Resonance (NQR)," A. N. Garroway, M. L. Buess, J. B. Miller, B. H. Suits, A. D. Hibbs, G. A. Barrall, R. Matthews, and L. J. Burnett, Invited article for IEEE Transactions on Geoscience and Remote Sensing **39**, 1108-1118 (2001).*

"Circularly Polarized RF Magnetic Fields for Spin-1 NQR," J. B. Miller, B. H. Suits, and A. N. Garroway, Journal of Magnetic Resonance **151**, 228-234 (2001).*

"Three-frequency Nuclear Quadrupole Resonance of Spin-1 Nuclei," K. L. Sauer, B. H. Suits, A. N. Garroway, and J. B. Miller, Chemical Physics Letters **342**, 362-368 (2001).

"Secondary echoes in three-frequency nuclear quadrupole resonance of spin-1 nuclei," K. L. Sauer, B. H. Suits, A. N. Garroway, and J. B. Miller, Journal of Chemical Physics **118**, 5071-5081 (2003).

"¹⁴N magnetic resonance for materials detection in the field," B. H. Suits, A. N. Garroway, J. B. Miller, and K. L. Sauer, Solid State Nuclear Magnetic Resonance **24**, 123-136 (2003).

"Optimizing surface coils and the self-shielded gradiometer," B. H. Suits and A. N. Garroway, J. Applied Physics **94**, 4170-4178 (2003).

"The Noise Immunity of Gradiometer Coils for ¹⁴N NQR Land Mine Detection: Practical limitations," B. H. Suits, Applied Magnetic Resonance **25**, (*accepted for 2004 publication*).

New Invention Disclosure(s) submitted:

"Improved RF Gradient Coil for Measurements in the Field," A. N. Garroway and B. H. Suits, Navy Case Number 84,294. Patent application submitted by NRL, Sept 2003, under the title "Radiofrequency Surface Detection Coil."

Presentations (by Suits) at Scientific Meetings:

"Some Aspects of Coil Design for NQR Land Mine Detection," B. H. Suits, J. B. Miller and A. N. Garroway, International Meeting on the Advances in NQR Detection of Land Mines and Explosives, Ljubljana, Slovenia, June 2000.

"N-14 Magnetic Resonance in the Solid State," B. H. Suits, the 2002 Midwest Regional American Chemical Society Meeting, Ypsilanti, MI, June 2002.

"Optimized, self-shielded, one-sided, surface coil for magnetic resonance in the field," B. H. Suits and A. N. Garroway, (Poster Presentation) Magnetic Resonance Gordon Research Conference, RI 2003.

"Advances in Spin-1 NQR for Explosives Detection in the Field: Implications for NQR Imaging," B. H. Suits, A. N. Garroway, J. B. Miller, and K. L. Sauer, 7th Int. Conf. On Magnetic Resonance Microscopy (ICMRM), Snowbird, Utah, Sept 2003.

"Gradiometer coils and land mine detection," NRL Mini-symposium - "Detection by Magnetic Resonance," Arlington, VA, January 2004.